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Astrometric confirmation of a wide low-mass companion to the planet host star HD 89744

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Abstract. In our ongoing deep infrared imaging search for faint wide secondaries of planet-candidate host stars we have confirmed astrometrically the companionship of a low-mass object to be co-moving with HD 89744, a companion-candidate suggested already by Wilson et al. (2000). The derivation of the common proper motion of HD 89744 and its companion, which are separated by 62.996±0.035 arcsec, is based on about 5 year epoch difference between 2MASS and our own UKIRT/UFTI images. The companion effective temperature is about 2200 K and its mass is in the range between 0.072 and 0.081 $M_{\odot}$, depending on the evolutionary model. Therefore, HD 89744 B is either a very low mass stellar or a heavy brown dwarf companion.

Key words: stars: low-mass, brown dwarf — stars: individual (HD 89744)

1. Introduction

Up to now precise radial velocity (rad-vel) searches have studied approximately 2000 sun-like stars and found so far more than one hundred extra-solar planets (Lineweaver&Grether 2003), some of which are found in stellar binary systems (e.g. Naef et al. 2003). The planets found in the binaries are most intriguing, because they provide the possibility to study the effect of stellar multiplicity on the planet formation and the long-time stability and evolution of planetary orbits (Zucker & Mazeh 2002).

Companions close to the planet-hosting stars (closer than 100 AU) can be detected either indirectly by rad-vel measurements (e.g. Korzennik et al. 2000) or directly by high resolution speckle (e.g. Neuhäuser et al. 2000) or adaptive optics (AO) imaging (e.g. Patience et al. 2002). Wide companions, with separations larger than 100 AU, lie outside the field of view (FOV) of AO systems, and can not be detected by rad-vel variation, because of their long orbital periods. Such companions are, however, reachable by wide field imagers but so far the whole sample of extra-solar planetary systems has not been surveyed homogeneously for wide companions with sensitive IR cameras. We therefore initiated a systematic search for wide faint companions to all stars known to have rad-vel planets, using relatively large IR images with up to 150 arcsecs FOV. The intrinsic faintness of low-mass companions can be confirmed by spectroscopy, and their companionship can be established by detecting proper motion equal to that of the planet-hosting star, which usually has large proper motion ($\mu \sim 200$ mas/yr) well known due to precise measurements of the European astrometry satellite *HIPPARCOS*. The first result of our project is presented here.

A faint wide candidate for a companion of one of the stars orbited by a planet was already suggested by Wilson et al. (2001), who searched the 2MASS database for red companions to nearby stars. They found a very red object close to HD 89744, which is now known to have a planet with a minimum mass ($msin(i)$) of 7.2 M_{Jup} a period of 256 days with a semi-major axis (a) of 0.88 AU on a very eccentric orbit, with $e = 0.7$ (Korzennik et al. 2000). Wilson et al. obtained a spectra of the faint object and derived a spectral type of L0V. Although the 2MASS photometry is consistent with a L0V object at the distance of HD 89744, the companionship could not be established beyond any doubt without further astrometry that will show that the two objects share the same proper motion. This paper presents astrometric observations that show that the faint companion of Wilson et al.

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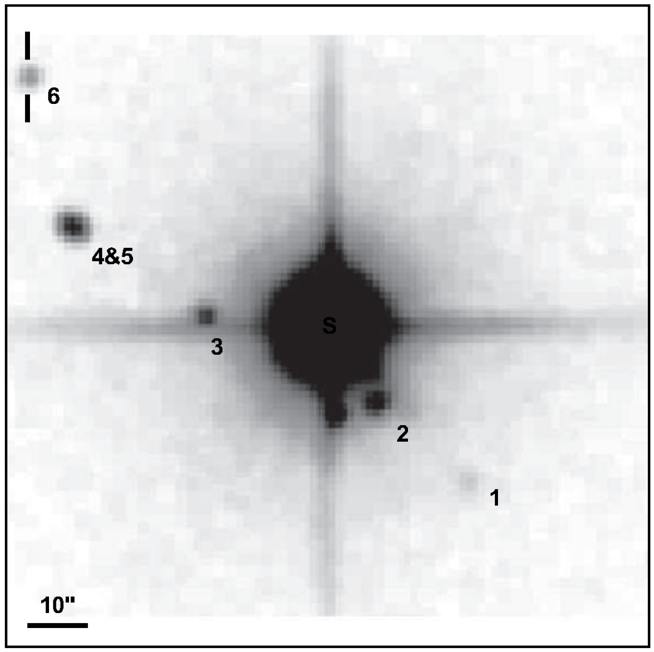
does indeed move with the same proper motion as HD 89744, establishing the physical association of the two stars.

2. Observations and Data Reduction

All observations of our program were done in the H-band (1.6 μm), because late-type stars and substellar objects are much brighter in near IR than in the visible bands, and IR detectors available today offer sufficient sensitivity. Therefore the contrast between the bright primary (hot) and a low-mass close-in companions (cool) is less prominent in the near infrared than in the visible, rendering the companion detection in the IR possible. Observations were made at the United Kingdom Infrared Telescope (UKIRT) with the IR camera *UKIRT Fast-Track Imager* (UFTI), a 1024×1024 HgTeCd-detector with a pixel resolution of 90.85$\pm$0.2 mas/pixel, i.e., 93 arcsecs FOV. UFTI can detect an $H \sim 20$ mag star in 10 min total integration time (see sect. 5).

We used sky-flatfielding to correct the different pixel sensitivity and the standard IR imaging jitter technique for background subtraction. The flatfield image was composed of several images of a faint (not saturating) standard star. The integration time must be long enough (> 10 s) to get a good sky background signal which can be used as skyflat. The standard star was observed on different chip positions (jitter-technique). A point spread function (PSF) was fitted to this star and it was subtracted from the individual images. The PSF subtracted images contained only information of the chip illumination and were median combined to create the flatfield image. Both flatfielding and background subtraction were carried out using ESO package *ECLIPSE*, with which we also combined all the reduced frames into the resulting image. Due to the brightness of the planet-hosting star we had to use short integration times, in order to minimize saturation effects. With a 4s integration time (the shortest possible UFTI integration time) saturation occurred only in the central region of the stellar PSF. The raw images were nearly background limited (6s with UFTI at UKIRT), which gave us a good sensitivity for faint wide companions. Observations were made with a 8-point-jitter cycle on the IR detector. To reduce the overhead, on each jitter-position six short 4 s integrations were added, hence 24 s total integration time per jitter-position. We repeated the 8-point-jitter cycle three times hence 3x(8x24 s)=576 s total integration time per target.



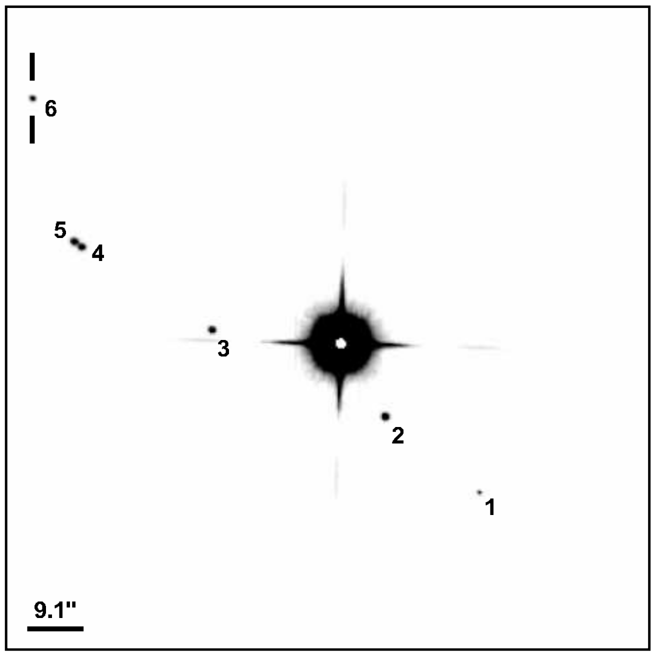


Fig. 1. H-band images of HD 89744. Top — 2MASS image (1998), bottom — UFTI image (2003) . North is up and east to the left. The bright rad-vel planet host star is located in the center of the image. Several companion-candidates are detected. The co-moving companion HD 89744 B can be found in the upper left corner of the images (candidate 6).

3. Astrometry

We have obtained two H-band images of HD 89744 with UFTI in June 2002 and June 2003. Several companion-candidates are detected in the images, all with S/N>>10. Figure 1 shows one of these images, together with a previous IR observation of HD 89744 which had been taken by the Two Micron All Sky Survey (2MASS) in April 1998. Three objects are listed in the 2MASS point source catalog, namely the companion-candidates 1 and 6, together with HD 89744 itself.

By using the separations in the 2MASS image as a starting value and using *HIPPARCOS* data for the parallactic and proper motion of HD 89744, one can determine the expected separations between the candidates and HD 89744 for our two epochs, assuming the candidates are non-moving background stars. Physical companions should have same proper motion as the primary, therefore their position relative to the primary should be constant. We can neglect orbital motion here, because for wide companions (a>100 AU) it is much smaller than the proper and parallactic motion.

Table 1. Table of observations

instrument	epoch	pixelscale (arcsec)	FWHM (arcsec)
UFTI/UKIRT	05/06/02	0.09085	0.64
UFTI/UKIRT	10/06/03	0.09085	0.55

The expected positions of candidates 1 and 6, both as co-moving and as background objects, are shown in Fig. 2 & 3, together with the actual separation of the two objects. The distance between HD 89744 and candidate 1 became smaller between 1998 and 2003, exactly as predicted by the *HIPPARCOS* data of the primary. Hence companion-candidate 1 is a non-moving background star. On the other hand, the distance between HD 89744 and candidate 6 remained constant within the astrometric precision in all three epochs. We therefore conclude that candidate 6 is a co-moving companion to the planetary system. Consequently, candidate 6 must be physically associated with HD 89744, because the chance to find a fore-/background object with exactly the same proper motion is negligible. Candidate 6 has common proper motion (CPM) with HD 89744 and will be denoted as HD 89744 B in the following.

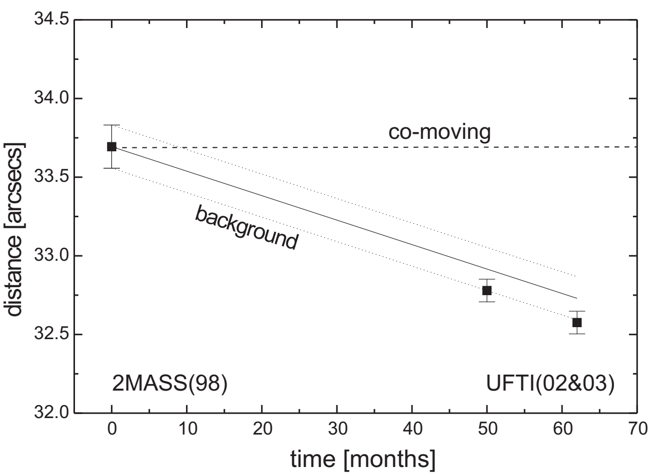


Fig. 2. The measured separation between HD 89744 and the companion-candidate 1 for 2MASS (1998) and UFTI (2002 & 2003) images. The separation (black data points) becomes smaller exactly as it is predicted by the parallactic and proper motion of HD 89744 (see full line), hence this candidate is a non-moving background star.

The two UFTI observations taken with only one year apart, the data from the 2MASS point source catalogue and the 2MASS image itself can be used to check whether any of the remaining detected candidates 2, 3, 4 or 5 are co-moving with the planetary system. In Table 2 we have listed the results of the astrometry test for these candidates. Candidates 2 and 3 do not move together with HD 89744. While the evidence for candidate 2 is quite strong ($\sim 7\,\sigma$ confidence level), the evidence for candidate 3 is not that conclusive (only $\sim 2\,\sigma$ level) by using only our UFTI images. Candidate 3 is not listed in the 2MASS point source catalogue but is well separated from the primary in the 2MASS image (see Fig. 1). We measure the positions of both objects in the 2MASS image and get a separation of 19.925±0.148 arcsecs for the epoch 1998. Hence with the 2MASS image and our UFTI images we can conclude that candidate 3 is also a none-moving background star with a confidence level of $\sim 5\sigma$. The Table 2 shows that candidates 4 and 5 do not move relative to candidate 3.

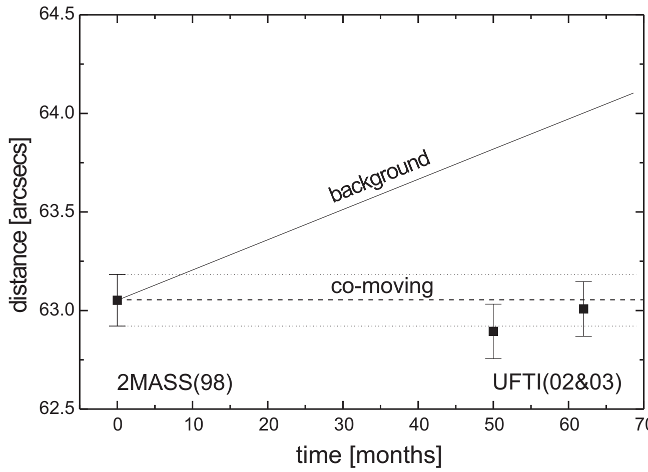


Fig. 3. The separation between HD 89744 and the companion-candidate 6. The measured separations (black data points) are constant for the given range of time. Therefore, candidate 6 is co-moving with HD 89744.

Table 2. Astrometry for the two UFTI observations. The separation between all detected objects is listed. The motion of the star is clearly detectable (see S-2 and S-3 for separation between the primary star (S) and the companion-candidates 2 and 3, respectively). The separations 3-4, 3-5 and 4-5 are constant for both epochs.

objects	separation 2002 (arcsec)	separation 2003 (arcsec)
S-2	13.913±0.031	13.688±0.031
S-3	20.620±0.045	20.720±0.046
3-4	24.771±0.055	24.747±0.055
3-5	26.186±0.058	26.176±0.058
4-5	1.418±0.012	1.432±0.012

4. The Nature of the two Members of the Common Proper Motion Pair

HD 89744 is a F7V (B-V=0.531) star located at a distance of 39±1 pc (Perryman 1997). Its mass is 1.4±0.2 (see Allende Prieto & Lambert 1999; Ng & Bertelli 1998; Feltzing 2001; Chen & Zhao 2002, Laws 2003; Santos 2004; Fuhrmann 2004). The stellar age ranges from 2 to 3 Gyrs (see Marsakov 1995; Feltzing 2001; Ibukiyama 2002; Chen 2002; Laws 2003). With $[Fe/H]$ = 0.18 (Taylor 2003) HD 89744 is a bit more metal rich than the sun, a frequent feature for stars hosting rad-vel planets (Udry&Mayor 2002).

2MASS photometry of HD 89744 B in the J,H and K bands and the distance to HD 89774 yielded absolute near IR magnitudes for the faint companion, all given in Table 3. Our relative aperture photometry of our UFTI images is consistent with the H band mag of 2MASS, within the photometry precision (see Table 3).

Table 3. 2MASS photometry for HD 89744 B and the calculated absolute magnitude in J,H and K. In H we show also the UFTI photometry results.

band	app. magnitude (mag)	abs. magnitude (mag)
J	14.901±0.037	11.946±0.071
H	14.022±0.033	11.067±0.071
H_{UFTI}	14.070±0.052	11.115±0.080
K	13.608±0.039	10.653±0.072

Several evolutionary models for low-mass stars, brown dwarfs and planets are available today that can determine the faint object mass and effective temperature from the obtained absolute photometry. Table 4 shows the results of three models from Baraffe (1998 and 2003) and Chabrier et al. (2000), namely BCAH98, DUSTY00 and COND03. For BCAH98 we used the model with mixing length of $\alpha = 1.0$, He abundance $Y = 0.275$ and solar metallicity $[M/H] = 0$, because it is the only set available for low-mass objects down to 0.072 $M_\odot$. Table 4 shows results of all models for an age of 1 and 5 Gyrs. For an age of 1 Gyr HD89744 B has an averaged mass of 0.076 $M_\odot$ and an effective temperature of 2200 K, whereas for 5 Gyrs one gets m = 0.079 $M_\odot$ and $T_{\rm eff}$ = 2200 K (average of $T_{\rm eff}$ always rounded to nearest 100 K). Therefore we can conclude that the co-moving companion HD 89744 B is either a heavy brown dwarf or a very low-mass stellar companion.

Table 4. The mass and effective temperature of HD 89744 B. Models used were BCAH98, DUST00 and COND03 for 1 and 5 Gyrs. Values of $T_{\rm eff}$ always rounded to nearest 100 K.

model	mass ($M_\odot$)	$T_{\rm eff}$ (K)
	*** age 1Gyr ***	
BCAH98	0.074±0.002	2200
DUSTY00	0.077±0.002	2200
COND03	0.076±0.003	2300
	*** age 5Gyr ***	
BCAH98	0.078±0.001	2200
DUSTY00	0.080±0.001	2200
COND03	0.078±0.003	2200

5. Discussion and Conclusion

By measuring the spatial noise level in the two UFTI images we can determine the UFTI detection limit (see Fig. 4). $H \sim 20$ mag is reached in the background noise dominated region, which allows us to find even substellar companions down to 0.040 $M_\odot$ assuming a conservative star age of 5 Gyrs and use Baraffe COND03 models. Closer to the star the detection limit is worse due to the increasing photon noise of the nearby bright star. With the given UFTI detection limit shown in Fig. 4 and the results from the UFTI astrometry in sec. 3 we can conclude that there is no further stellar companion around HD 89744 A from 144 AU (3.7 arcsecs) up to 1891 AU (48.5 arcsecs), which is the maximal FOV completely covered by both UFTI images. Further wider companions can be detected up to 2573 AU ($\sim$ 66 arcsec) but only 64% of this larger FOV is covered by the UFTI detector.

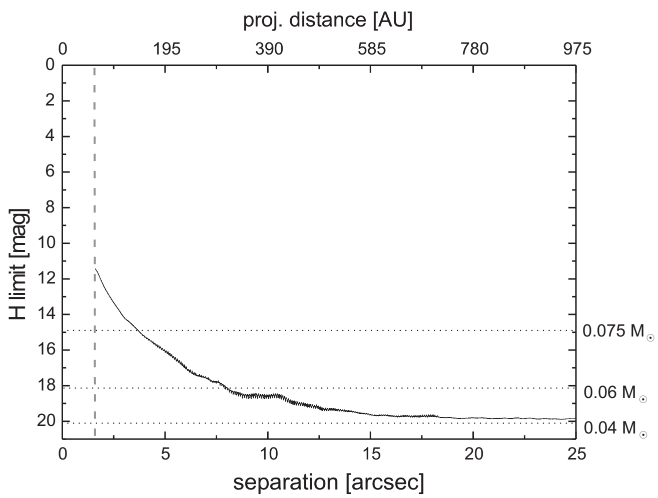


Fig. 4. The UFTI detection limit (S/N=3) for a range of separations. The averaged FWHM of all detected objects is $\sim$0.6 arcsecs. Inside a radius of 62 AU ($\sim$1.6 arcsec) around the bright rad-vel planet host star saturation occurs. This part of the detector cannot be used for companion detection and is excluded in the plot. The detection of all stellar companions down to 144 AU ($\sim$ 3.7 arcsec) is possible. We assumed a conservative system age of 5 Gyrs and used Baraffe COND03 models for the magnitude-mass conversion.

Can we detect the orbital motion of HD 89744 A and B? The angular separation between the two of them is 62.996±0.035 arcsec, i.e., 2456±67 AU projected separation. For a = 2500 AU and a total mass of about 1.4 $M_\odot$ the orbital period is approximately 10^5 years, hence too long to detect any astrometric or rad-vel orbital motion.

Finally we can estimate limits of long-term stability criteria for further undiscovered companions in the HD 89744 system. Holman & Wiegert (1999) found a certain critical semi-major axis a_c for which circular orbits of test particles around the primary will be disrupted, depending on the eccentricity of the wide companion. This critical semi-major axis can be further reduced if the test particles themselves are on eccentric orbits. For a mass ratio $\mu = m_S/(m_P{+}m_S) = 0.1$ and a presumed circular orbit of HD 89744 B ($a{\sim}$2500 AU) we get $a_c{\sim}$ 1100 AU and $a_c{\sim}$ 100 AU for a very eccentric orbit with $e = 0.8$. However the mass ratio of the HD 89744 system ($m_P \sim 1.4\,M_\odot$ and $m_S \sim 0.077\,M_\odot \Rightarrow \mu = 0.052$) is smaller, i.e., a_c is even larger as calculated above. With

the Holman & Wiegert stability criteria we can conclude that further companions could reside within a 100 AU orbit even for very eccentric orbits of HD 89744 B. Those objects are detectable by AO search programs which are on the way. But so far no further low-mass companion is reported in the HD 89744 A&B system.

A few planet-hosting stars have faint companions like HD 89774. E.g. HD 114762, υ And and 55 CnC have common proper motion companions with projected separations of 131 ± 8 AU, 747 ± 8 AU and 1060 ± 13 AU respectively (separations determined with our images). The set of planets in wide binaries is still not complete, and therefore no comparison with planets in close binaries and around single stars is possible. Such a comparison might be possible when our systematic search would be complete.

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